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Application of the WetSpass simulation model for determining conditions governing the recharge of shallow groundwater in the Poznań Upland, Poland

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Abstract

Assessments of the infiltration recharge of groundwater are performed using various methods and on different scales. Infiltration is dependent of climatic factors, aspects of water circulation, as well as on quasi-stationary and variable environmental features of a specific area, which are frequently difficult to determine on the basis of direct measurements or observations. The objective of the present study was to identify factors conditioning recharge of shallow groundwater in selected catchment areas of the Poznań Upland using the WetSpass simulation water balance model with spatially distributed parameters. Our analysis has indicated favourable and unfavourable conditions for recharge of groundwater in the annual period and in both half-year periods, which are the result of mutual relationships between the physical qualities of these catchment areas and their climatic and hydrological characteristics. The results obtained also confirmed the impact of surface runoff and actual evapotranspiration on the spatial distribution of effective infiltration. With soil types and groundwater depth distributions being similar in the catchment areas, changes in relationships between components of water balance are caused by differences in the type of land usage. Application of the WetSpass model has made it possible to arrive at a more accurate assessment of groundwater recharge. The results obtained may be used for erification of recharge areas and values of effective infiltration, set as a boundary condition in groundwater flow models.

Key words: shallow groundwater recharge, water balance, lowland catchment

1. Introduction

The recharge system of a catchment area is a complex aggregate, described by a specific number of diagnostic variables. Spatial relationships between selected variables, both quantitative and qualitative, illustrate the state of the active surface of a given catchment area with regard to the distribution of rainwater and infiltration recharge of shallow groundwater (Blöeschl, 2001; Graf, 2012; Graf & Przybyłek, 2014). In view of the fact that this is a process that varies over time and space, infiltration is dependent of climatic factors, aspects of water circulation, as well as quasi-stationary and variable environmental features of a specific area, which are frequently difficult to determine on the basis of direct measurements or observations. Research into the infiltration recharge of groundwater stresses the problem of the uncertainty of estimation of its magnitude when complete data are unavailable and point data cannot be transformed to a recharge field (Sophocleous, 1992).

Hydrological processes occurring in the catchment are highly dynamic and the aspect of their continuity or discontinuity presents a significant problem in their description and visualisation to represent the spatial and temporal relationships between them. Estimation of water balance components, which consists in selecting the right input data and boundary conditions, assumes the creation of a model with the lowest possible number of defining variables (Soczyńska, 1997; Batelaan & De Smedt, 2001; Dąbrowski et al., 2011; Graf, 2012). The conceptual model of the groundwater recharge process accounts for the aspect of identification of the scale of the hydrological process, inlets and outlets of the water circulation system as well as its temporal and spatial limitations, such as an area's infiltration predisposition and the type or character of a hydrologically active zone (Yair & Kossovsky, 2002; Dripps & Bradbury, 2007; Sorooshian & Hsu, 2008; Graf & Przybyłek, 2014).

A model with spatially distributed parameters (i.e., a raster model) provides information on the diversity of effective infiltration, as well as precipitation, effective infiltration, surface runoff and evapotranspiration, whose spatial distribution is assigned to raster cells with a homogeneous structure, which function as balance cells. The significance of the impact of climatic and environmental factors is defined by the scale of a particular study (Ozga-Zielińska & Brzeziński, 1997; Blöeschl, 2001; Singh & Frevert, 2006; Graf, 2012)

The objective of the present study was to identify factors conditioning the infiltration recharge of shallow groundwater in selected catchment areas of the Poznań Upland using the WetSpass water balance model with spatially distributed parameters. The purpose of the application of WetSpass model was to calculate the volume of infiltration recharge and indicate the reference area of shallow groundwater recharge while assessing its dominant and accessory characteristics. Simulations of the infiltration recharge of rainwater took into consideration the dependencies that existed between physiographic features of the catchment areas and depth to the water level, in relation to climatic factors and the process of surface runoff and evapotranspiration.

2. Methodological approaches to assessing recharge of groundwater

Assessments of the recharge of groundwater are performed using various methods and on different scales of elaboration (Batelaan, 2006; Graf, 2012; Jaworska-Szulc, 2015; Tarka et al., 2017). Among others, physical, marker, water balance and mathematical process modelling methods are used (Table 1). A broad review of the methods and techniques used for estimating the recharge of groundwater has been provided, among others, by Lerner et al. (1990), Scanlon & Cook (2002), Scanlon et al. (2002), Batelaan (2006) and Healy (2010). As far as Poland is concerned, on regional and local scales, reference is made to papers by Pleczyński (1981), Jokiel (1994), Graf (2012), Herbich et al. (2013) and Staśko (2017).

Assessments of the infiltration recharge of groundwater make broad use of methods which model hydrological processes and the spatially distributed water balance model of the catchment area (Table 1). Of considerable significance for the execution of models of this type is the compilation of various types of topical data illustrating features of the reference surface (the so-called active surface) for the infiltration supply of water, e.g., soil types, hypsometric conditions, land usage and depth to the groundwater table (Brun & Band, 2000; Lee & Heaney, 2003; Band et al., 2005; Batelaan, 2006; Graf, 2012; Graf & Kajewski, 2013; Graf & Przybyłek, 2014; Kajewska et al., 2017). In models that take into consideration the process of water and energy exchange between various elements (among others: atmosphere, soil and vegetation), the infiltration recharge of precipitation is calculated in relation to the remaining components of the water balance in its distributive part, i.e., surface runoff or subsurface outflow and evapotranspiration (Van de Giesen et al., 2000; Wainwright & Parson, 2002; Yair & Kossonsky, 2002; Cherkauer & Ansari, 2005; Dripps & Bradbury, 2007).

Studies of the recharge of groundwater conducted in areas with diverse climatic and environmental conditions, e.g., different types of soils and land usage and variable hydrogeological conditions, have contributed to the development of methods of its estimation based on statistical analyses and classifications utilising GIS techniques and teledetection (Sophocleous, 1992, 2005; Sophocleous & Perkins, 2000; Batelaan & De Smedt, 2001; Batelaan, 2006). Furthermore, use is also made of hybrid models and various geoinformational techniques which make it possible to integrate hydrological models with numerical flow models and groundwater monitoring systems (Gurwin, 2010). Research conducted by Callahan et al. (2012) and Nolan et al. (2018) emphasised the importance of the integration of data concerning shallower and deeper systems of circulation of groundwater in analyses of determinants of the process of their recharge, which has a significant impact on the reliability of the results obtained.

Table 1. Selected methodological approaches for assessing recharge of groundwaters.

Method	Interpretations and references
Physical methods (models)	Approximate: e.g. Green & Ampt (1911), Philips (1957) and empirical models e.g. Kostiakov (1932), Horton (1941); US-Soil US-Soil Conservation Service (SCS) model
Statistical methods (models) and artificial neural networks	Statistical models: models for estimating cumulative infiltration (Zolfaghari et al., 2012; Rahmati, 2017), multi-linear regression model (Sihag et al., 2017a), support vector regression-based modeling (Sihag et al., 2018), Gaussian process regression (Sihag et al., 2017b) Artificial neural networks: Nestor (2006), Tiwari et al. (2017)
Infiltration methods, effective infiltration coefficient	Empirical effective infiltration coefficient, Classifications binding the infiltration coefficient with the rock type: Załuski (1973), Pazdro & Kozerski (1983), Paczyński et al. (1996), Tarka (2001), Scanlon & Cook (2002), Duda & Paszkiewicz (2009), Herbich et al. (2009), Śmietański (2012), Herbich et al. (2013), Staśko et al. (2013), Sitek & Ulańczyk (2016), Czyżyk & Świerkot (2017), Tarka et al. (2017)
Water table fluctuation methods	Identification of the state of retention of the free-surface aquifer: Pleczyński & Przybyłek (1974), De Vries & Simmers (2002), Herbich et al. (2013), Graf (2012)
Hydrological methods	The opposite equivalent of effective infiltration is the coefficient of subsurface outflow (base flow) calculated on the basis of flows in the water-gauge section with long-term observations of water level (Wundt, 1953; Kille, 1970; Pleczyński, 1981; Pazdro & Kozerski, 1983; Herbich et al., 2013)
Methods based on isotopic indicators (marker method) and chemical indicators	Identification of the subsurface component of river run-off on the basis of isotopic and chemical indicators. Analysis of environmental markers (e.g., the content of tritium and freons in water) in order to determine the average age of groundwater (Zuber, 2007)
Balance methods	1. Groundwater balance – limited to the subsurface phase of water circulation within the range of the water-bearing system of the catchment area. Calculations of effective rainwater infiltration are based on the river-channel and evapotranspirational identification of groundwater discharge in river valleys (Walton, 1970; Pazdro & Kozerski, 1983; Macioszczyk, 2006; Herbich et al., 2013). 2. Water balance of the catchment area – the equation concerns the estuarial section of the river (Ozga-Zielińska & Brzeziński, 1997; Soczyńska, 1997)
Hydrological modelling	1. Rainfall-outflow model: – WetSpa: Water and Energy Transfer between Soil, Plants and Atmosphere - The department of Hydrology and Hydraulic Engineering Vrije University in Brussel: Porretta-Brandyk et al. (2010), Choromański & Michałowski (2011), Piniewski & Okruszko (2011) – Soil and Water Assessment Tool (Neitsch et al., 2004; Neitsch et al., 2005) – MIKE SHE (Systeme Hydrologique European), integrated system modeling the water cycle (Ozga-Zielińska & Brzeziński 1997; Singh & Frevert, 2002; Singh & Frevert 2006; Sorooshian & Hsu, 2008) 2. The spatially distributed water balance model – WETSPASS - Water and Energy Transfer between Soil, Plants and Atmosphere under Quasi–Steady State (Batelaan & De Smedt, 2001; Kajewski, 2004; Pokojska 2004; Batelaan & Woldeamlak, 2007; Choromański & Michałowski, 2011; Piniewski & Okruszko, 2011; Graf, 2012; Graf & Kajewski, 2013; Graf & Przybyłek, 2014)
Mathematical modelling of the groundwater flow	The infiltration recharge of groundwater is insufficiently identified, and is determined in the course of calibration (MODFLOW) - (Szymanko, 1980; de Vries & Simmers, 2002; Scanlon et al., 2002; Dąbrowski et al., 2011)

3. Study area

The catchment areas (859 km^2) of three tributaries of the River Obra were selected for research; those of rivers Dojca, Szarka (the Szarkowski Trench) and Czarna Woda (Fig. 1), each with surface areas of between 251 and 338.5 km^2, which form part of the catchment area of the River Warta. Their characteristic feature is a considerable fraction of sandy soils in the lithology of surface formations, which constitutes an advantageous infiltration type (Table 2). Their greatest percentage fraction is in the catchment area of the River Czarna Woda (65%). The catchment areas differ in terms of land usage, particularly as far as the proportion of forest complexes in total surface area is concerned, while they have a similar content of zones with low and moderate terrain slopes (up to 2.5°).

The rivers drain primarily the Poznań Upland (Kondracki, 2008), the topographic profile of which

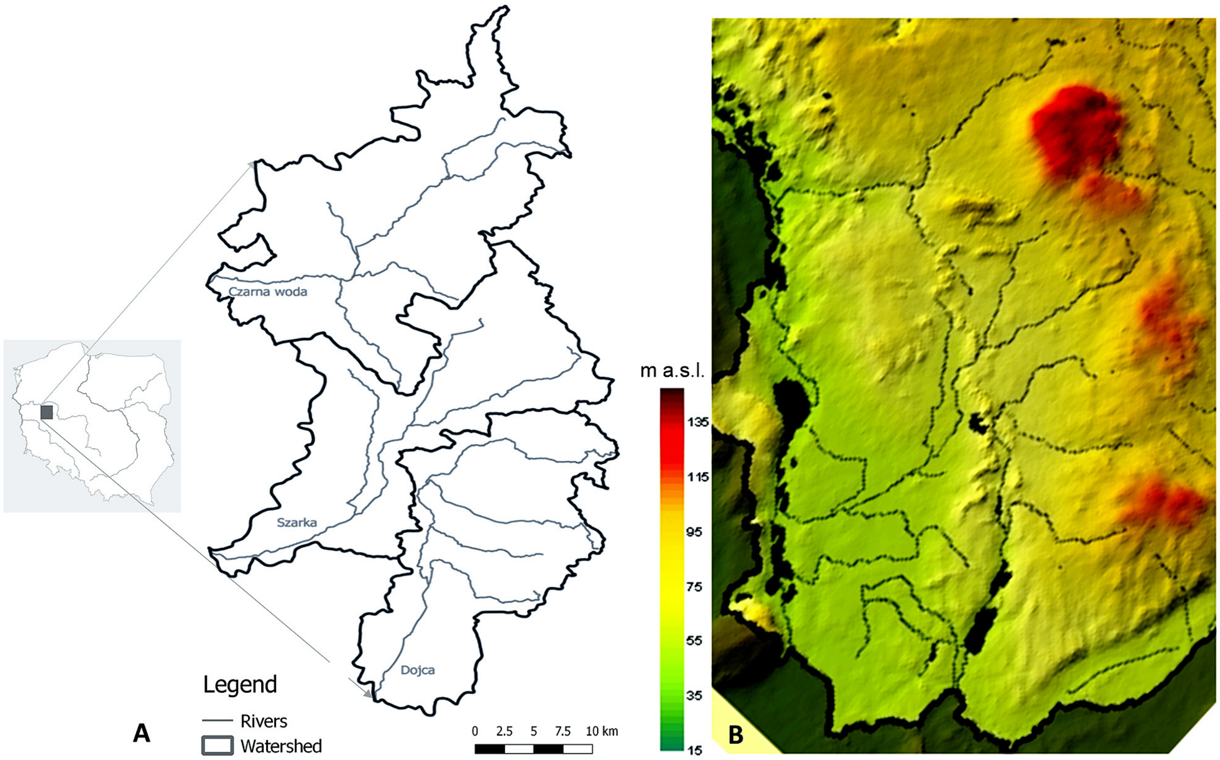

Fig. 1. Location of the area analysed using the digital model.

is the product of Pleistocene and Holocene morphogenesis, while the segmentation of the terrain was influenced to a considerable extent by sculpturing processes associated with the Poznań and Leszno phases of the Wisła Glaciation (SMGP 1:50,000). The test area covers a large portion of the so-called Nowotomyski Outwash (the Nowotomyska Plain) and the Obra Valley within reach of the Zbąszyńska Furrow (the rivers Szarka and Czarna Woda) and the Warsaw-Berlin Glacial Valley (the catchment area of the River Dojca) and this is reflected in the spatial distribution of the physico-geographical features of the catchment area. The outwash plain constitutes a relatively flat area – with heights ranging from 60–70 to 105 m above sea level – bisected by a network of water courses. The topographic profile is made varied by dune embankments with relative heights up to a dozen or so metres and deflation troughs (Fig. 1). The outwash neighbours on a clay morainal upland (the Opalenicka Plain) and the meridionally oriented form of morainal Lwówecko-Rakoniewicki Embankment, which culminates at 137.8 m above sea level.

With regard to the regional division of groundwater (Paczyński & Sadurski, 2007), the test area is located in the lowland subregion (SWN) of the Warta region (RW). The shallow groundwater forms a level in the sand-gravel formations of valley benches, urstromtal benches (0–2 m) and outwash plains (2–5 m, locally 5–10 m) (Dąbrowski, 1990; Graf, 2012). The groundwater recharge takes place through the effective infiltration of precipitation. The catchment areas analysed are located within the Western Greater Poland climatic regions, where the average annual air temperature totals 8.3°C (Woś, 2010). The low precipitation (500–550 mm), accompanied by high evaporation (450–500 mm), negatively impacts the structure of the water balance, which is reflected in the low recharge values of shallow groundwater (1.0–2.0 dm^3/s/km^2) and low specific runoff from the catchment areas (q = 2.5–3.0 dm^3/s/km^2) (Graf, 2012).

4. WetSpass simulation model

The spatial determinants of the infiltration recharge of shallow groundwater in catchment areas were assessed using the WetSpass (*Water and Energy Transfer between Soil, Plants and Atmosphere under quasi–Steady State*) model, which is intended for area simulation of water balance on a regional or local scale under quasi-steady state conditions (Batelaan & De Smedt, 2001). The model integrated with GIS in raster data format utilises a number of empirical dependencies occurring between the atmosphere and the soil and plant environment with regard to the exchange of water and energy, simulating the spatial distribution of the infiltration recharge of precipitation, surface runoff and actual evapotranspiration in relation to terrain factors and average hydrometeorological conditions (Fig. 2). The model constitutes an example of the method of estimating elements of the area water balance which requires the integration of meteorological, hydrological, topographical, soil, land coverage and land usage data in the GIS environment. The structure of the model makes possible the compilation of data with other models, e.g., the numerical model of filtration of groundwater.

In the WetSpass model, the infiltration recharge of groundwater is estimated from the balance difference as a function of vegetation, soil texture, terrain inclination, groundwater depth and the precipitation regime for average conditions for a year and for the winter and summer half-year periods. Calculations of infiltration recharge refer to individual (raster) balance cells which represent a specific type of reference surface: covered with vegetation, without vegetation coverage and for an impermeable (insulated) surface (Fig. 2). The WetSpass model enables to obtain a legible spatial distribution of values of effective infiltration for various soil and land usage types, which may be utilised as reference features for calculations in other balance models.

The water balance of the catchment areas was simulated at the level of raster cells with a size of 250 x 250 m. The multi-annual period 1961–2000 was adopted as the reference period, and this ensured the homogeneity of thematic and hydrometeorological data for the catchment areas selected. The quality of the model was verified by estimating the modelling error (+/– mm) in annual and seasonal simulations. The results of infiltration recharge received through the WetSpass model were verified by a comparison with the results of simulations of groundwater flow carried out using the *Processing Modflow for Windows* (PMWIN, Version 5.3.0) model (Graf, 2012). To this end a comparison was made of the value of infiltration with values of subsurface runoff to water courses which were obtained through the MODFLOW model, assuming that this originated primarily from the infiltration recharge of shallow water-bearing levels. The PMWIN model was described in detail by Chiang & Kinzelbach (2001) and Kulma & Zdechlik (2009).

4.1. Source materials and input data

When selecting input elements for the WetSpass model (Fig. 2), use was made of digital topical GIS databases and a model of the topographic profile. The information layer for basic ground (soil) types with ID codes assigned in the WetSpass model was created through the schematisation of soil conditions and the aggregation of spatial data from the Detailed Geological Map of Poland (*Szczegółowa Mapa Geologiczna Polski*, abbreviation *SMGP*, PIG-

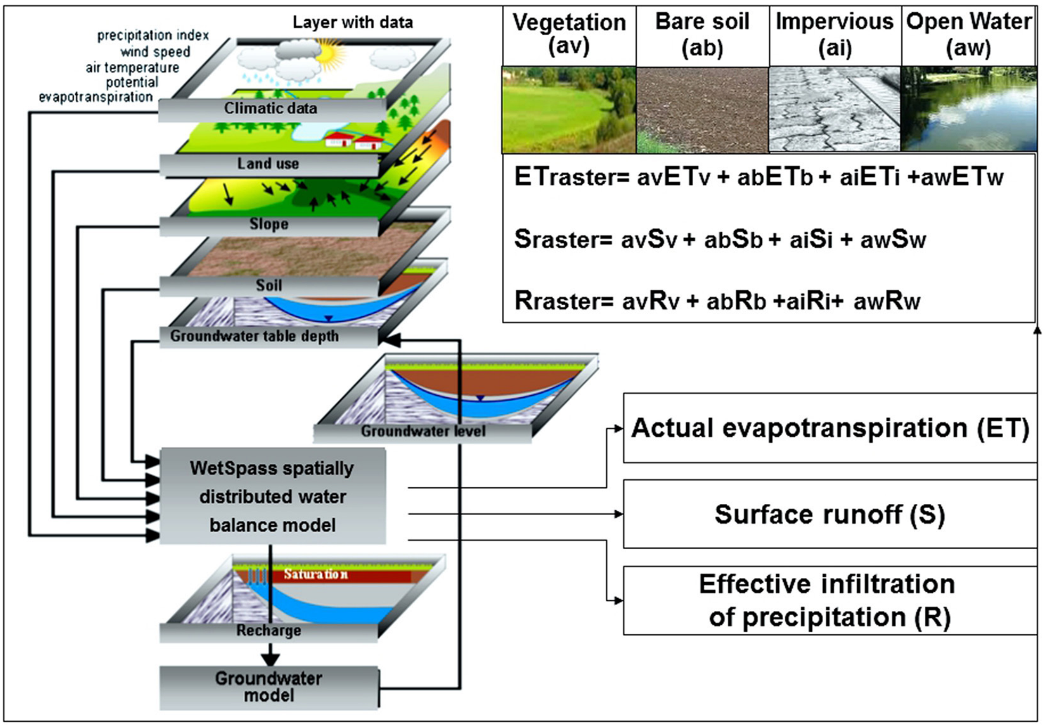

Fig. 2. Conceptual diagram of the WetSpass model (modified after Batelaan & De Smedt, 2001; Graf & Przybyłek, 2014).

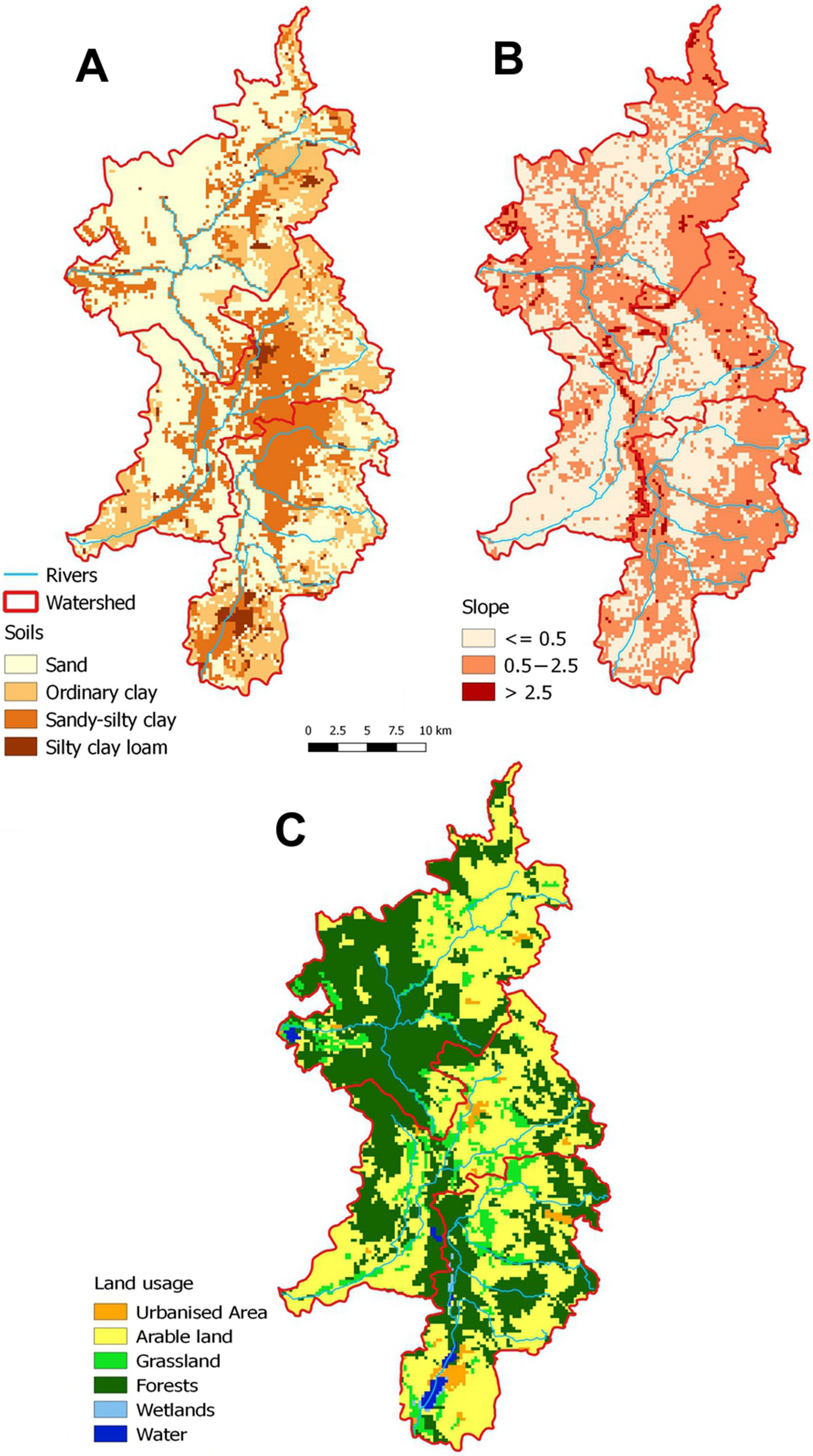

Fig. 3. Spatial models of selected diagnostic variables of the catchment areas; input data for the WetSpass model: **A –** soil type; **B –** terrain slope [degree]; **C –** land usage.

PIB) and the Hydrographic Map of Poland 1:50,000 (GUGiK). Terrain slope was analysed on the basis of a numerical model of the topographic profile DTED 2 according to the PUWG 1992 co-ordinate system. Information on land coverage and usage was taken from the CORINE Land Cover (CLC, 2000) data base. The study of the spatial distribution of the depth of the water level of shallow groundwater made use of maps of hydroisobaths from the digital GIS hydrographic data base, with the information being converted to regionalised data. These data were supplemented with descriptions of the features of their regimes, obtained from the permanent groundwater measuring network of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB).

Average precipitation in the catchment areas and its spatial distribution were estimated on the basis of precipitation maps elaborated for the region of the Poznań Upland for the period 1961–2000 (Graf, 2012). A similar procedure was applied in order to estimate the spatial distribution of air temperature and wind velocity and potential evapotranspiration. Potential evapotranspiration was determined using the Penman-Monteith method (FAO-PM, 1998), with meteorological data for the Poznań station (1961–2000) being used in calculations.

The input data base for simulation studies using the WetSpass model comprised raster maps: of ground (soil) types, of terrain slope and land usage and of the depth to the groundwater level (Figs. 3–4). In addition, maps of area-averaged sums of precipitation, potential evapotranspiration, air temperature and wind velocity were elaborated for three calculation variants (year, winter half-year period, and summer half-year period), in line with assumptions of the model (Fig. 2). A detailed description of the criteria according to which source materials were selected and spatial data elaborated for the WetSpass model can be found in the works of Batelaan & De Smedt (2001) and Batelaan & Woldeamlak (2007), while for the region of the Poznań Upland the study by Graf (2012) was consulted.

In the catchment areas studied, sandy soils with an average permeability predominate, while the share of formations with a lower permeability is connected with the presence of a clayey moraine upland. Typically, the test area has zones with a terrain slope of up to 2,5°, while the proportion of zones with an increasingly greater slope continues to fall (Fig. 3). More sizeable terrain slopes have been recorded in the watershed zones of the catchment areas and in the esker and kame hillock and inland dune structures.

In general, two types of land usage are predominant in the area: agriculture and forestry. However, their fraction of the surface of individual catchment areas varies (Table 2). Arable land predominates in the catchment areas of the rivers Szarka and Dojca, with the surface occupied by forests being decreased by a proportion of 1.5 and 1.2, respectively. However, forest complexes are predominant in the usage structure of the River Czarna Woda catchment area, even though the content of arable land

Table 2. Selected physico-geographical features of the catchment areas: number of raster cells, features.

Features	Dojca		Szarka		Czarna Woda	
	Number of cells raster	%	Number of cells raster	%	Number of cells raster	%
			Soil types			
Sand	1791	44.5	1997	46.3	3519	65.0
Clay	843	21.0	961	22.3	896	16.5
Sandy-silty clay	1216	30.2	1251	29.0	924	17.1
Silty-clayey loam	173	4.3	103	2.4	77	1.4
			Land cover and usage			
Arable area	1956	48.6	2324	53.9	2168	40.0
Grassland	308	7.6	356	8.3	306	5.6
Urbanised area	128	3.2	66	1.5	34	0.63
Forests	1530	38.0	1555	36.1	2891	53.4
Water	72	1.8	11	0.25	17	0.31
Wetlands	29	0.72	0	0	0	0
			Terrain slope			
< 0.5°	1551	38.6	2417	56.0	3038	56.1
0.5–2.5°	2398	59.6	1746	40.5	2193	40.5
> 2,5°	74	1.8	149	3.5	184	3.4
Area sum:	4023 (251 km^2)	100.0	4312 (269.5 km^2)	100.0	5416 (338.5 km^2)	100.0

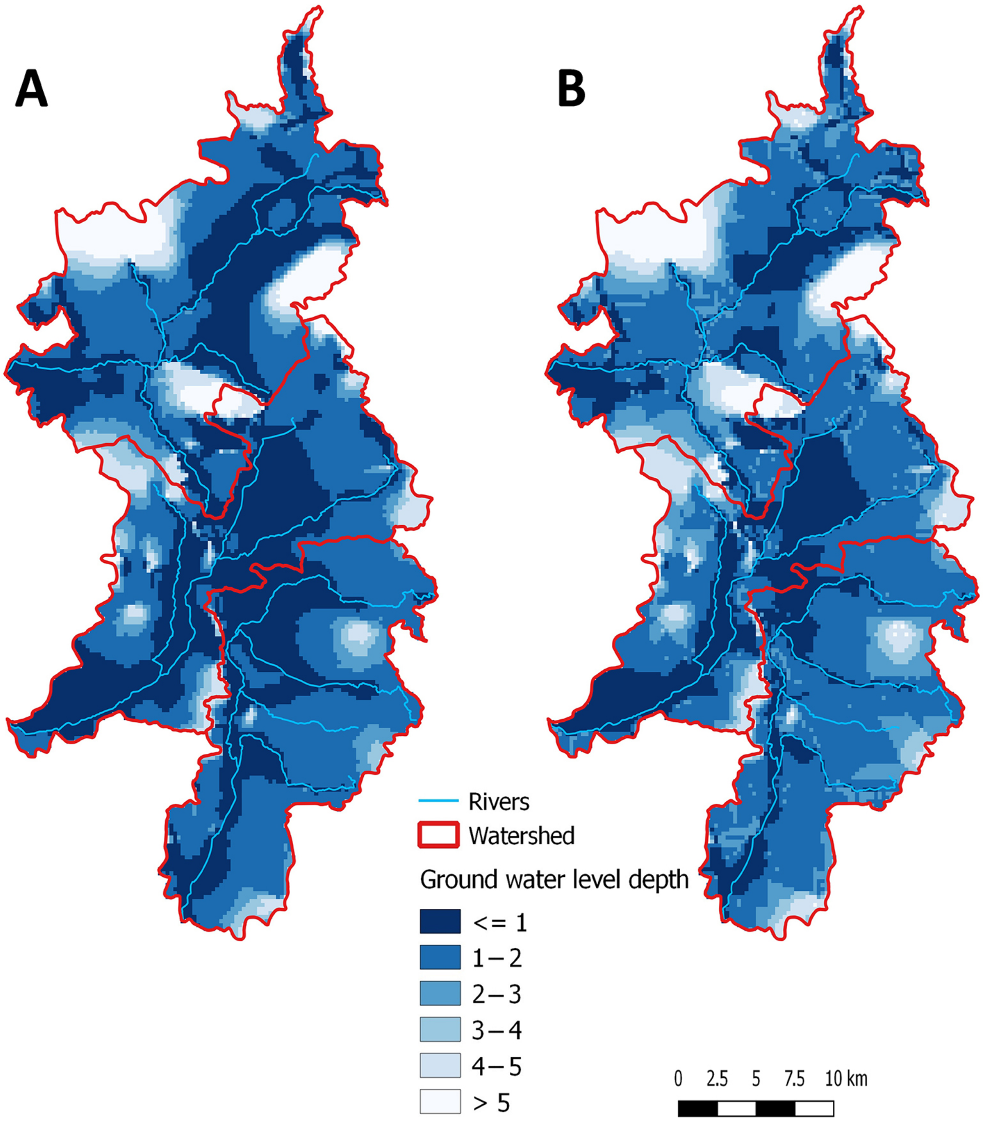

Fig. 4. Spatial distribution of the depth of shallow groundwater [m]; input data for the WetSpass model: **A –** winter half-year period; **B –** summer half-year period.

in its northeastern part remains considerable. The spatial distribution of forest complexes shows that they are more segmented in the catchment areas of the rivers Szarka and Dojca (Fig. 3).

The catchment areas are dominated by zones (approximately 48% in the summer half-year period and 80% in the winter half-year period) in which, under average conditions, the depth of groundwa-

Table 3. Water balance components for the catchment areas obtained through the WetSpass model for average conditions in the annual period and in the summer and winter half-year periods.

Catchment area		Year				Winter half-year				Summer half-year			
		P*	IE	Hp	ET	P	IE	Hp	ET	P	IE	Hp	ET
Dojca	mm	535	74	39	427	212	119	14	79	323	–45	25	348
	%	100	13	7	80	100	56	6	38	100	–	8	108
Szarka	mm	535	82	35	419	214	126	10	78	321	–44	24	341
	%	100	15	6	79	100	59	5	36	100	–	8	106
Czarna Woda	mm	545	91	21	433	220	134	7	79	325	–43	15	354
	%	100	17	4	79	100	61	3	36	100	–	5	109

*P – precipitation, IE – effective infiltration, Hp – runoff, ET – actual evapotranspiration.

ter reaches up to 2 m (Fig. 4). Changes in amplitudes of fluctuation of the groundwater level between the winter and summer half-year periods total up to 0.5 m in the outwash and valley zones, and up to approximately 2 m in the upland zone.

5. Results of model studies

Calculations of the water balance for the catchment areas, carried out under the WetSpass model for three variants – annual balance, summer half-year period and winter half-year period, showed a slight diversification of components on the inflow side. Differences in precipitation are small, ranging from a few to 10 mm, while higher average sums of precipitation were determined for the catchment area of the River Czarna Woda (Table 2). The proportion of the infiltration recharge of shallow groundwater in the average annual balance totals 13–17%, of surface runoff 4–7% and of actual evapotranspiration 79–80%. In the annual water balance, the average infiltration recharge of precipitation ranges from 74 mm (catchment area of the River Dojca) to 91 mm (catchment area of the River Czarna Woda). Similar relationships were determined for the balance for the winter half-year period, when the recharge of groundwater is intensified, while its share in the structure of the balance in the catchment areas ranges from 56 to 61% (Table 2). During the winter season relationships between components of the balance change – effective infiltration increases at the expense of evapotranspiration and surface runoff, which are both limited.

When compared with the water balance for the winter half-year period, that elaborated for the summer half-year period shows that, in the main, water losses are connected with evapotranspiration (transpiration of plants, evaporation from soil, interception), while the infiltration recharge of groundwater is limited or comes to a halt altogether. During this period evapotranspiration exceeds precipitation, and thus the balance is negative. A comparison of balances for the annual period and the summer half-year period indicates that the simulations have led to obtaining slightly higher values of total evapotranspiration in the catchment area of the River Czarna Woda (Table 3).

Simulations of the infiltration recharge of groundwater conducted for average conditions from a multi-annual period have demonstrated differences in spatial distribution (Fig. 5). The annual balance is dominated by zones with an infiltration recharge of 60–80 mm (catchment area of the River Dojca) and of 80–100 mm (catchment areas of the rivers Szarka and Czarna Woda). During the winter season an increase in the share of zones with an infiltration of 130–140 mm (catchment areas of the rivers Dojca and Szarka) and of 140–150 mm (catchment area of the River Czarna Woda) occurs (Fig. 6). The greatest recharge of groundwater during the winter season takes place in the watershed zones of the catchment area of the River Czarna Woda, whereas in the same period the two other catchment areas are characterised by a similar spatial distribution of infiltration recharge (Fig. 5).

The soils most susceptible to infiltration recharge of groundwater in the catchment areas analysed are sands of varied granularity, for which the highest average values of infiltration recharge have been obtained in the annual balance, and also in the balance for the winter half-year period (with the maximum in excess of 150–160 mm; see Fig. 7). Dusty and silty clays, in turn, are characterised by unfavourable conditions for the recharge of groundwater.

As far as types of land usage are concerned, conditions conducive to the infiltration recharge of shallow groundwater have been determined in the annual balance for arable land (90–110 mm) and slightly less favourable for forested areas (approximately 70–80 mm). In the winter half-year period, in light of the decrease in evapotranspiration, opportunities for infiltration increase in forested areas, grasslands and arable land. Due to their high potential for transpiration and interception processes, which are activated in particular in the summer season, forest complexes lower the retention component of the annual water balance. This is confirmed, among others, by researchers including Sophocleous & Perkins (2000), Batelaan (2006), Okoński (2006) and Graf (2012).

A comparison of two variables, namely soil types and land usage, has shown that the most favourable conditions for the recharge of shallow groundwater occur on arable land with a predominance of sandy formations and grasslands (Table 4). After additionally taking into consideration terrain slopes and the depth to groundwater table in the catchment areas as their reference surfaces (i.e., the ones that condition the structure of the water balance), arable land was distinguished in areas with average permeability, with slopes of up to 0.5° and with a shallow occurrence of groundwater (up to 2 m), which occupy approximately 12–15% of the surface. The second dominant type of reference surface, particularly in the catchment area of the River Czarna Woda (approximately 15%), are forest complexes standing on soils with an average

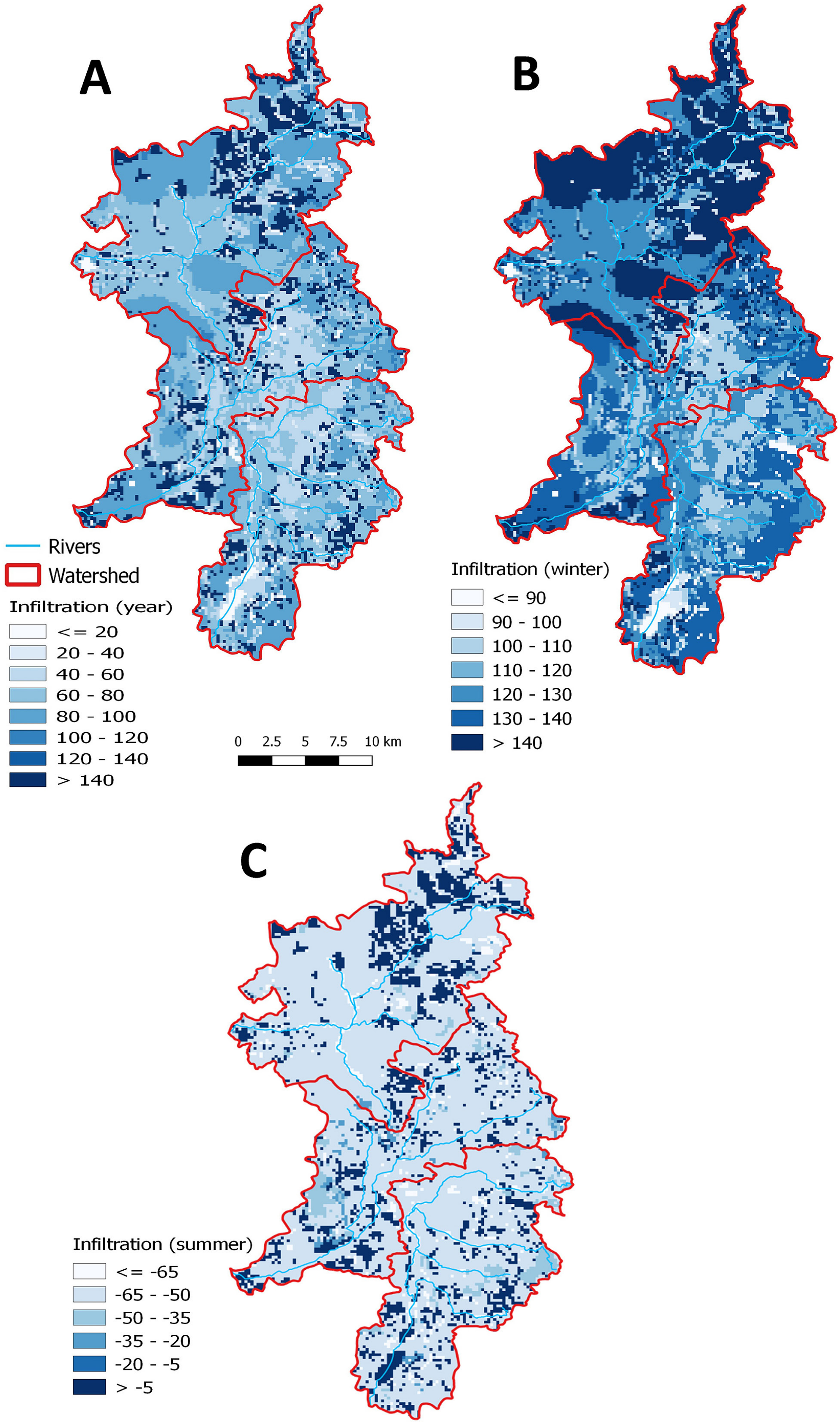

Fig. 5. Spatial distribution of average infiltration recharge of shallow groundwater in the catchment areas studied [mm]; results of the WetSpass model: **A** – year; **B** – winter half-year period; **C** – summer half-year period.

permeability, small (up to 0.5°) or moderate slopes (0.5–2.5°) and groundwater at a depth of 2–5 m. For the zones thus distinguished, the average values of infiltration recharge estimated under the WetSpass model for annual conditions totalled 60–80 mm; in other words, they were similar to the average values calculated in water balances for the catchment areas (Table 2).

The result of infiltration recharge obtained in the water balance of the catchment areas may be equated with the value of subsurface runoff, while its spatial distribution may, with reference to the diverse types of surface infiltration, be used to calculate values for the Modflow groundwater flow model in the water-bearing layer.

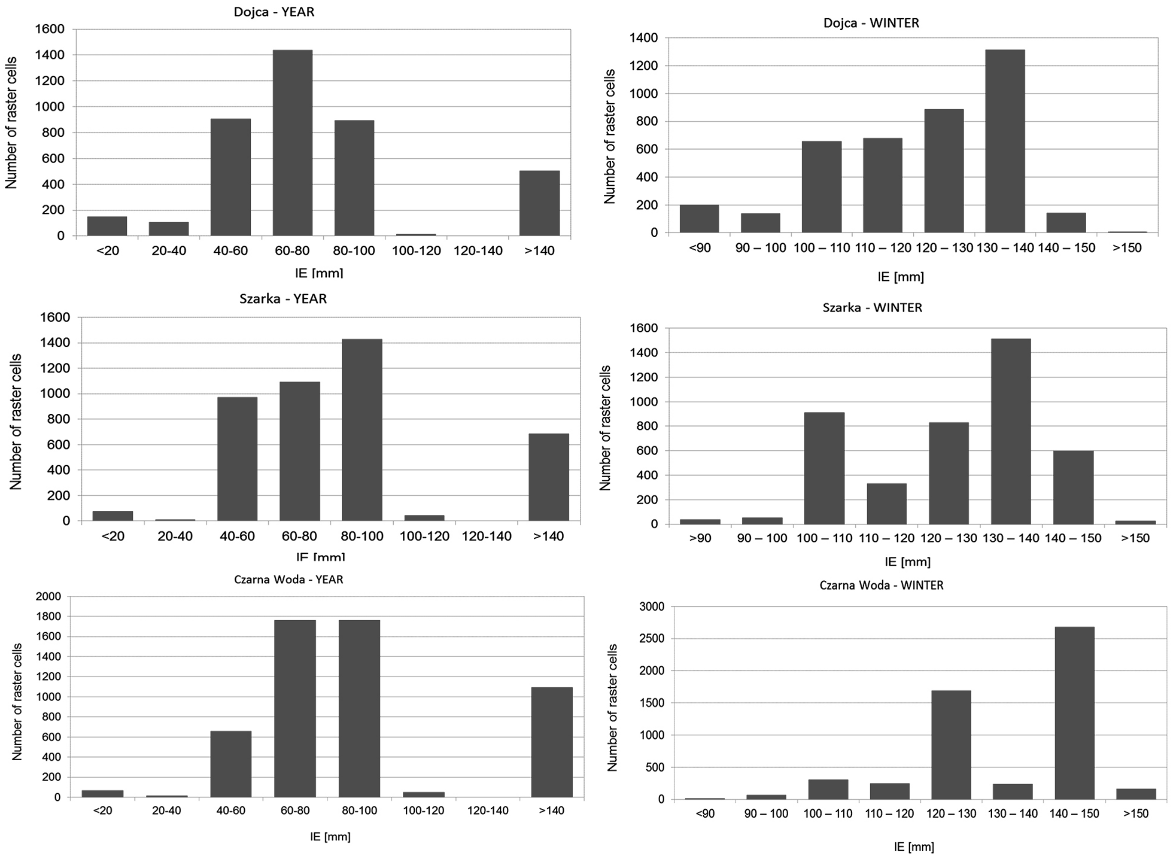

Fig. 6. Histograms of distribution of zones with an average value of infiltration recharge in the basic balance cell for the annual period and the winter half-year period.

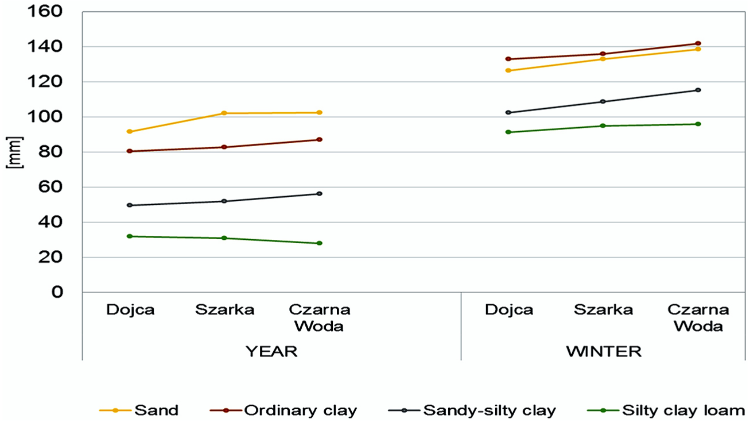

Fig. 7. Average values of infiltration recharge for individual soil types in the catchment areas studied, received in the annual balance and in the balance for the winter half-year period under the WetSpass model.

Table 4. Values of infiltration recharge [mm] for reference surfaces represented by soil and land usage types in the catchment areas studied, obtained in the annual balance – results from the WetSpass model.

Ground (soil) types	Land cover and usage	Dojca	Szarka	Czarna Woda
Sand	Urbanised area	18	15	0
	Grassland	156	156	161
	Forests	70	78	79
	Arable area	146	148	155
Ordinary clay	Urbanised area	88	87	91
	Grassland	85	86	92
	Forests	72	78	81
	Arable area	82	84	90
Sandy-silty clay	Urbanised area	46	72	72
	Grassland	68	65	73
	Forests	42	49	45
	Arable area	49	49	54
Silty-clayey loam	Urbanised area	46	43	43
	Grassland	13	10	0
	Forests	30	39	33
	Arable area	16	18	19

Note: the colour assigned to a value denotes the intensity of the process of effective infiltration: red – intensive groundwater recharge, orange – moderate process, green – weak process.

6. Discussion

Methods of assessing the spatial properties of catchment areas based on GIS systems, of which the WetSpass model used in the present study is one, make it possible to identify their parameters to a degree that is sufficient to conduct spatial analyses of both local and regional water circulation conditions, including infiltration recharge (Sophocleous, 1992, 2005; Batelaan & De Smedt, 2001; von Asmuth & Maas, 2001; Jackson, 2002; Batelaan, 2006; Thangarajan, 2007). In local water circulation, the effective infiltration of precipitation constitutes the main source of recharge for shallow groundwater (80–90% of total recharge) (Graf, 1999, 2012; Graf & Przybyłek, 2014). The process of groundwater recharge takes place within different levels of intensity of the entire catchment area, becoming scattered or point-based; this has been confirmed by models with spatially distributed parameters elaborated for the catchment areas of the rivers Czarna Woda, Szarka and Dojca. Model studies conducted on the area of the Poznań Upland indicate that the recharge of shallow groundwater takes place throughout the catchment areas, being conditioned by their shallow occurrence and the lithological and infiltration features of superficial formations (Graf, 2012).

The inclusion in the WetSpass model of relations between physiographical features of the catchment areas and climatic and hydrological factors made it possible to distinguish the predominant type of active surface (hydrologically active) and the zones predisposed to increased infiltration recharge of groundwater (Fig. 5). Areas containing permeable formations which are not isolated from the surface of the land by a layer of units of low permeability with a very low topographic and hydraulic gradient were identified as preferential. In the catchment areas studied, the zone of groundwater recharge varies strongly in terms of hypsometry. Among others, dune embankments and numerous depressions with no outlets are present (Fig. 1) and these can locally increase the value of infiltration recharge (absorptive depressions) or serve to limit it, as is the case with evapotranspirational depressions.

Under conditions of oceanic regime, the infiltration recharge of shallow groundwater occurs primarily in the winter season, at the expense of limiting evapotranspiration, which in the summer season in turn considerably reduces the process of recharge (Chełmicki, 1991; Graf, 2012). This has been confirmed by simulations of the water balance carried out in the catchment areas analysed using the WetSpass model. An example of the seasonality of the recharge regime of shallow groundwater are fluctuations of their levels, which attain a maximum in the winter half-year period (Graf, 2012; Graf & Przybyłek, 2014). During this time, the proportion of infiltration recharge in the water balance of the catchment areas studied increases to more than 50% in relation to the summer period, as is indicated by the results of the WetSpass model (Table 3). Since the value of actual evapotranspiration in the catchment areas is similar, changes concern relationships between effective infiltration and the value of surface runoff; this is impacted to a considerable degree by the soil type and the method of land usage.

In the summer season there is a reduction or indeed a complete lack of infiltration recharge of groundwater, which development is associated with the high transpiration of plants, particularly in areas characterised by the shallow occurrence of groundwater, which in the study area have been found to include grasslands (Figs. 3, 5). According to Batelaan (2006), more than 55% of annual evapotranspiration is accounted for by transpiration, which is predominant in zones overgrown with vegetation, while lesser significance is attached to evaporation from uncovered soils and interception. In central Greater Poland, the lowering of the

Table 5. Results of groundwater balance modelling in catchment (Processing Modflow PMWIN model) [mm].

Catchment	Infiltration recharge by WetSpass	Subsurface inflow	Discharge	Subsurface outflow	Inflow vector Σz	Outflow vector Σo	Difference ± σ
Dojca	74.1	12.1	74.4	11.8	89.1	86.2	–2.9
Szarka	81.7	0.8	76.0	6.6	82.5	82.7	–0.2
Czarna Woda	91.0	1.3	75.1	17.3	92.3	92.4	–0.1

groundwater level in the summer season is facilitated by prolonged periods without precipitation (sometimes lasting over a month) and frequent droughts (Farat, 2004; Woś, 2010; Przybyłek & Nowak, 2011).

Assuming that the values of infiltration recharge obtained in the water balance for the catchment areas may be equated with subsurface runoff, a mutual verification was conducted of results from the WetSpass model and those from the Processing MODFLOW for Windows groundwater flow model (Graf, 2012) (see Table 5). In the assessment of subsurface inflow into local water circulation systems, it was assumed that it originated for a large part from the infiltration recharge of shallow aquifers. In the cases analysed the discharge of groundwater by water courses comprises the value of infiltration recharge (in approximately 60–70%) and the value of subsurface inflow from without the system of the catchment areas. During the period of summer–autumn low waters the subsurface supply of water courses takes place under conditions of limited infiltration of precipitation and increased evapotranspiration, coming mainly from water resources retained in the winter half-year period. The PMWIN models developed for the catchment were found to be reasonable, obtaining the compatibility reconstruction of the shallow groundwater table with an accuracy of 0.5 m (Graf, 2012).

In mathematical groundwater flow models the conditions of circulation of waters are determined by the structure and hydrodynamic state of the system, and also by the zones of their recharge and discharge. The WetSpass model, in turn, simulates the areal distribution of the infiltration recharge of groundwater, while at the same time taking into account the relationship between the physiographic features of the catchment areas and climatic factors, as well as the process of surface runoff and evapotranspiration. Thanks to such a compilation of data, it provides data on the impact of individual subsystems of the catchment areas on the spatial distribution and value of effective infiltration, which may be used to verify areas of the infiltration recharge of groundwater, set as a boundary condition in groundwater flow models. In the presence of an appropriate data base, this compilation of results may constitute the basis for assessing the rechargeability of groundwater and conducting an analysis of its diversity in the spatial arrangement of the water-bearing system (Dąbrowski et al., 2011).

The values of groundwater infiltration recharge obtained in the catchment areas studied are typical of the region under discussion. The results are similar to values of infiltration for water-bearing levels calculated while using the mathematical groundwater flow modelling method, which have been broken down and described for the region by, among others, Dąbrowski (1990, 1995). Similar values have been obtained for the infiltration recharge of shallow groundwater on the basis of model studies performed at individual catchment areas by Kaniecki (1982) and Graf (1999). A comparison of the spatial distribution of infiltration recharge for the catchment areas of the rivers Dojca, Szarka and Czarna Woda determined on the basis of simulations carried out under the WetSpass model with the distribution of this component of the water balance calculated by Staśko et al. (2013) using the infiltration method also supports the conformity of the results obtained.

The image of the shallow groundwater depth (WetSpass model) was referred to the map of the Wielkopolska Lowland infiltration types and methods of fluctuating the groundwater table (Żurawski, 1966). The effective infiltration coefficient which was determined in the model as the average value, being reduced in relation to potential possibilities determined with a geological infiltration method by about 5–10% on average, extremely 20–30% (built-up areas).The range of variability of extreme infiltration values is also changed. In built-up areas with diversified degrees of soil permeability, the precipitation infiltration coefficient obtains very low values which are similar to clays or no infiltration recharge takes place. These areas showed a high predisposition to generate surface runoff which is confirmed by results obtained in other studies (Graf, 2012).

7. Summary

1. Application of the WetSpass model has made it possible to determine conditions governing the infiltration recharge of shallow groundwater in

catchment areas of the Poznań Upland. With the soil types and distributions of groundwater depths being similar in the three catchment areas, changes in relationships between components of the water balance are caused by differences in the type of land usage and, albeit to a lesser degree, by terrain slope.
2. The results obtained have also confirmed the impact of surface runoff and actual evapotranspiration, estimated in the model, on the spatial distribution of the groundwater recharge. Effective recharge of groundwater, due to infiltration of precipitation, occurs in the winter season. The contribution of effective infiltration to the water balance structure in the winter season is more than 50–60%, whereas in the summer season we registered either a reduction or absence, which was related to high plant transpiration in areas with shallow groundwater occurrence. It was observed that forest areas, due to the high potential of transpiration and interception processes which area active particularly in the summer season, lowered the retention component in the annual water balance.
3. The fact that a greater number of variables and their interrelationships were taken into account in the WetSpass model, inclusive of a number of empirical dependencies relating to factors conditioning hydrological processes, has made it possible to obtain a more detailed assessment of the infiltration recharge of groundwater.
4. The model utilised in the present research integrates various types of spatial data concerning the catchment areas, and thus significantly impacts the reliability of results obtained. The raster structure of the WetSpass model makes it possible to connect GIS integrated data with numerical groundwater models. The results obtained may be used for the verification of recharge areas and values of effective infiltration, set as a boundary condition in groundwater flow models. Spatial information can be used in subsequent simulations with modification of the initial conditions, e.g., by defining the land cover (or climate conditions) variation.

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